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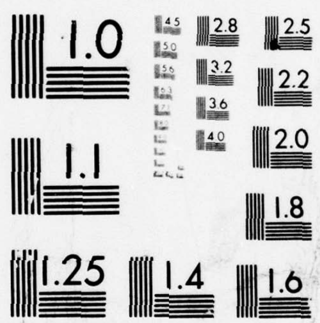

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

DELET-TR-78-30

DEVELOPMENT OF A FORTY KILOVOLT MEGAWATT AVERAGE POWER THYRATRON (MAPS-40)

J. Hamilton
S. Merz
R. Plante
D. Turnquist

EG&G, INC.

N. Reinhardt, Consultant
J. Creedon
J. McGowan

ELECTRONICS TECHNOLOGY & DEVICES LABORATORY

November 1978

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Abstract:

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The MAPS 40 embodies new engineering solutions to the problems encountered in high power thyratrons. In this development, careful attention had to be given to the control of operating dissipations, to the storage and dispersal of heat, to the strength and protection of internal tube structures, and to the special requirements of tube and circuit operation at the megawatt level.

In the first phase of the program, eight thyratrons were constructed, five of which were delivered to Fort Monmouth for evaluation. Four of these prototype tubes were tested to the specified objectives in short-burst operation, and were subjected to further tests to explore their nominal design capabilities. Seven more tubes have since been built, all of the same design, all of which have met the specified objectives.

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DEVELOPMENT OF A FORTY KILOVOLT
MEGAWATT AVERAGE POWER THYRATRON (MAPS-40)

J. Hamilton, S. Merz, R. Plante, and D. Turnquist
EG&G, Inc., Salem, Massachusetts

N. Reinhardt
Consultant, Lexington, Massachusetts

J. Creedon and J. McGowan
ETDL, USA ERADCOM, Fort Monmouth, New Jersey

Summary

The thyratron which resulted from the MAPS-40 Megawatt Average Power Switch development effort achieved switching of 40 kV and 40 ka with a pulse width of 10 microseconds and a repetition rate of 125 Hz. Operation was in 10- to 15-second bursts at the 1-megawatt average power level.

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In the first phase of the program, eight thyratrons were constructed, five of which were delivered to Fort Monmouth for evaluation. Four of these prototype tubes were tested to the specified objectives in short-burst operation, and were subjected to further tests to explore their nominal design capabilities. Seven more tubes have since been built, all of the same design, all of which have met the specified objectives.

Introduction

The MAPS-40 megawatt average power thyratron program is an outgrowth of the earlier MAPS-70 project, in which operation at several hundred kilowatts was achieved.[1,2] The work performed in this development relied heavily on advances made in earlier programs in extending operation to the present megawatt power level.

Specified objectives for the MAPS-40 thyratron are listed in Table 1. The operating condition features:

1. Operation at an epy level of 40 - 44 kilovolts.
2. Peak current of 40 kiloamperes.
3. Average current of 50 amperes.
4. An rms-equivalent current of 1480 amperes.
5. Repetitive burst mode operation, with "on" cycles of 3 to 30 seconds at the 1-megawatt average power level.
6. Restrictions on the number of missing pulses or kick-outs experienced during extended burst-mode operation.
7. A 48-hour standby requirement (heaters only).

Major problems were forward and inverse holdoff capability, aggravated by the standby requirement, and the thermal and mechanical design of heavy internal structures.

Table 1. Major specification objectives for MAPS-40 thyratron.

Parameter (Units)	Rating	Operation (1)	Operation (2)
epy (kV)	40	44	44
ib (ka)	40	44	11
egy (kV)	1.5-4.0	--	--
tp (μs)	--	10	20
prr (Hz)	500	125	250
Ib (A dc)	50	50	50
Ip (kA ac)	1.48	1.48	0.74
Pb (10^9 va/s)	400	242	[illegible]
dik/dt (ka/μs)	20	20	20
tad (μs)	--	0.2	0.2
Δtad (μs)	--	0.1	0.1
tj (μs)	0.02	--	--
Ef=Eres (Vac)	15±1.5	--	--
If (A ac)	70	--	--
Ires (A ac)	40	--	--
tk (sec)	900	--	--
Life (pulses)	--	5×10^6	5×10^6

Principal Design Considerations

A conventional external-anode, planar-electrode, ceramic-metal tube design was chosen to meet the basic design considerations for the MAPS-40 thyratron as outlined in Table 2. To obtain reliable, kick-out free operation at 40 - 44 kV, the use of a gradient grid was necessary. To prevent quenching, a large total grid-slot aperture area was required, implying an 8-inch diameter tube design. An auxiliary grid was necessary to obtain good triggering characteristics. To handle the operating dissipations at the cathode, a novel open-work type of vane structure was proposed.

Table 2. Principal design considerations.

Design Parameter	Area of Principal Concern	Design Decision
Electrical		
40 kV operation	Forward voltage hold-off, reliable operation.	Use gradient grid and tight baffling.
40 ka peak current	Grid aperture quenching.	Use 8-inch diameter tube.
High di/dt; low tad, Δtad and jitter.	Conflict with tight baffling of grids.	Incorporate auxiliary grid; use "keep-alive" bias.
1480a rms current.	Current distribution; ohmic heating in the cathode structure.	Careful attention to feeds and connections.
Burst-mode operation	Transient hydrogen cleanup.	Use fast-response reservoir.
High average power	Overheating.	Use composite construction of adequate thermal mass and conductivity: low thermal resistance from grids to external flanges.
Survival under arc-fault conditions	Melting of tube elements.	Molybdenum high-voltage surfaces: anode, grids, and shields.
Thermal and Mechanical		
8-inch diameter seals	Thermal stresses arising from bimetallic electrode construction.	Use compensation and stress relief techniques.
Burst-mode operation	Thermal runaway.	Absorption of heat followed by dispersal during "off" periods.
Deuterium Pressure Stability	Titanium reservoir temperature and rate of response.	Isolate reservoir from thermal surges in rest of tube; design for fast response.
Sagging, creep, warping	Complex and heavy mechanical parts made of ductile materials in grids, cathode, reservoir.	Brace structures with stiff framework of refractory metals.
Environmental		
Survival under shock and vibration	Tube envelope and structures.	Design for strength and stiffness.
Field Handling	Shipping, mounting, connecting.	Handling features planned as integral part of tube.

The most difficult design problems arose in the thermal and mechanical design of the tube structures. Massive internal structures were needed to carry currents and to absorb and distribute operating dissipations. These had to function without warping, local melting, or causing electron emission to occur in undesirable places.

The grids, for example, were designed as thick copper-molybdenum sandwiches to resist arc damage and to spread heat away from the grid slots and conduct it to the tube exterior. These sandwiches had to be prevented from warping, or from exerting powerful expansion forces on the ceramic-to-metal seals.

The cathode required that a kilogram of dead-soft nickel be supported well enough to prevent sagging, creep, or deformations from g-forces (all problems experienced in the earlier MAPS-70 cathodes). The early tubes in the MAPS-40 program were built with what was basically a structurally augmented MAPS-70 cathode; later tubes incorporated an entirely new design in which operating dissipations were minimized and the structure integrally braced.

The reservoir, designed for rapid response to pressure or heater power changes, likewise had to be protected against deformation and heater shorts, and it had to be isolated from thermal surges in the rest of the tube.

The tube envelope, used to transfer the grid-dissipation heat loads efficiently to the surrounding air, was designed to employ butt-seals to heavy 1/8-inch thick copper flanges and to nickel-iron alloy flanges. Figure 1 shows the external appearance of the finished tube.

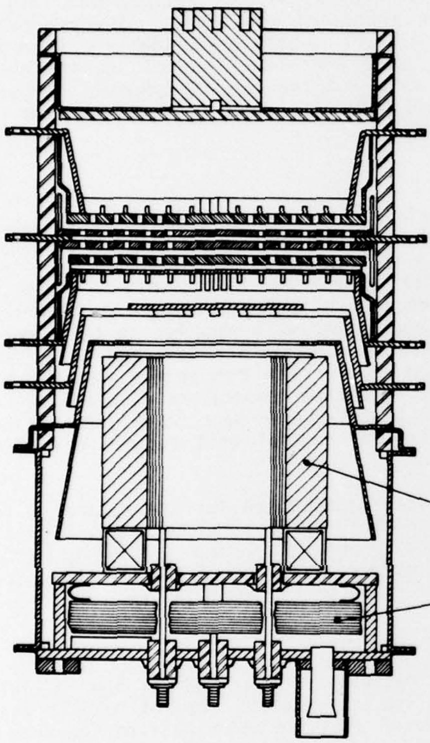

Figure 1. External view of MAPS-40 thyratron.

Significant Design Details

In tubes of this size and power level, it is necessary to carefully engineer many details of construction which can be left uncritically over-designed in smaller tubes. In the MAPS-40, many details were significant design problems, requiring that the tube electrodes and components be individually developed and tested separately to assure proper functioning as part of the complete tube.

Anode

Anode dissipation was assumed to be roughly 60% of that of the gradient grid, or about 1200 watts maximum. Its surfaces had to withstand potential arc damage and be suitable for maintaining high voltage holdoff.

In the MAPS-40 tube, inverse voltage holdoff was expected to be poor due to large peak currents and high di/dt required by the operating conditions. The use of a "virtual" anode, employed elsewhere and believed to act as its own inverse clipper, as well as to improve quenching characteristics, was considered as shown in Figure 2, and was tried on preliminary evaluation samples and on one actual early 8-inch diameter tube. Despite much effort, results proved negative or inconclusive, and this approach to the inverse holdoff problem was shelved. The virtual anode concept may offer some advantages, but its use was not pursued further in this program. The final tube design employs a conventional anode as shown in Figure 3. In this structure, a 3/16 in. thick molybdenum disk is supported by a tapered cup made from Driver Harris No. 146 alloy. A stepped shield of molybdenum surrounds the anode to prevent damage to the cup caused by discharges going up the side wall.

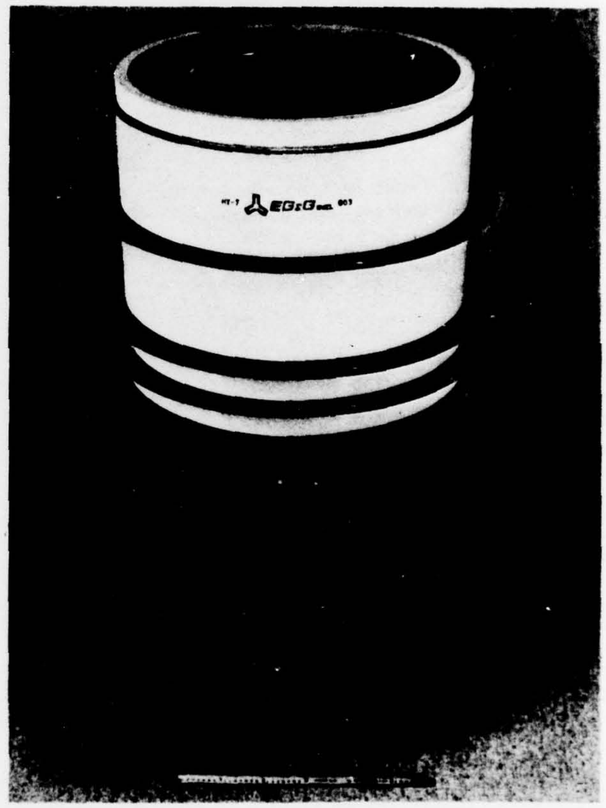

Figure 2. Trial version of MAPS-40 with virtual anode.

Gradient Grid

Of the alternative cavity and box-type grid designs depicted schematically in Figure 4, the box type was chosen because of its compact structure. Cavity-type grids imply longer, heavier structures and tend to exhibit poor recovery time.

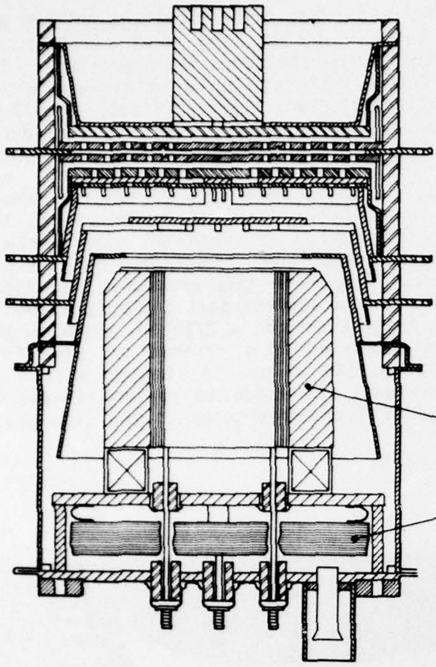

Figure 3. Cross section view of MAPS-40 with conventional anode.

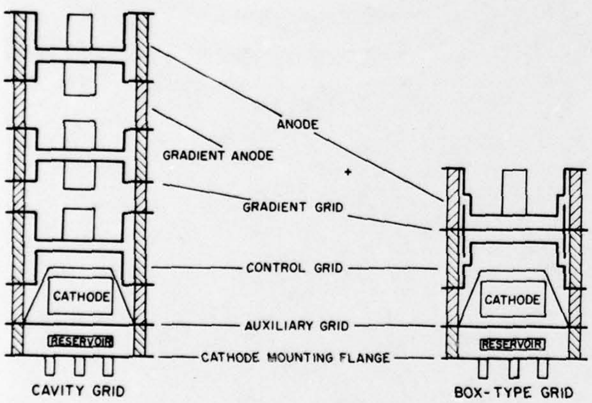

Figure 4. Comparison of cavity- and box-type grids.

Tight grid baffling was used to promote good forward holdoff. Molybdenum wall shielding was used to improve inverse holdoff capability and to increase quenching limits. For additional holdoff capability, the use of deuterium as planned in place of hydrogen as a fill gas. Gradient to control grid aperture offset was 0.110 in. Gradient grid to anode spacing was 0.125 in. Total grid aperture area was about 7.5 square inches, large enough to avoid quenching at the typical limit of 10 to 11 kiloamperes per square inch, a value confirmed experimentally early in this program. The aperture slots themselves were 0.155 in. wide, arranged as a concentric circular pattern of arc segments, a configuration found to give less heat buildup at the grid slot edges than a radial-slot layout with the same total aperture.

The mass and thermal conductivity of the grid were chosen so that the worst-case calculated grid dissipation (approximately 2000 watts) could be sustained for 30 seconds without causing more than a 250°C rise in average temperature. Overall grid thickness was 3/8 in., posing a formidable problem in accommodating differential thermal expansions. Strain-relief cuts and the use of deformable copper protect the ceramic-metal seal from failure due to these expansions.

Control Grid

Control grid dissipation was assumed to be higher than that of the gradient grid, to a maximum of about 3000 watts, due to power lost in the vicinity of the control grid baffle from the 30- to 50-volt Langmuir double-sheath drop to be expected where the discharge constricts. Copper bars were attached to the underside of the grid to increase its mass and to assist the radial heat flow, with the object, again, of restricting the operating temperature rise to 250°C. Slots were cut in the copper bars to provide strain relief. The conical control grid support was also made of copper.

The aperture pattern used for the control grid was identical to that employed in the gradient grid. Control-grid to grid-baffle, and control-grid to gradient-grid aperture offset was 0.110 in. Control-grid to gradient-grid spacing was 0.140 in.

Auxiliary Grid

The tight baffling of the gradient and control grid sections, used to promote forward holdoff and retard migration of emissive material from the cathode, was expected to have an adverse effect on triggering characteristics. Accordingly, it was decided to use an auxiliary grid, which could be supplied with "keep-alive" bias to shorten time of anode delay from hundreds to tens of nanoseconds, to stabilize delay-time drift, and to suppress jitter. The presence of the auxiliary grid would also aid recovery, help suppress cathode material migration, and most significantly, lower the heat load of the control grid by the interception and reflection of cathode power.

The auxiliary grid is a molybdenum plate connected by heavy copper heat-conducting bars to a copper support cone. A skirt keeps evaporated material off the ceramic insulator ring. The auxiliary grid is spaced from the control grid by about 5/8 in.

Cathode Baffle

The cathode baffle is basically a heat shield which intercepts power and evaporated material from the cathode. It is heavily constructed at the top to resist damage. Currently a single-layer structure, its dimensions are chosen to obtain a nominal cathode heater power requirement of 800-1000 watts. Its upper surface is spaced 1 in. away from the auxiliary grid, and about 1/4 in. away from the cathode vanes.

Cathode

The 5000 cm^2 cathode used in the earlier MAPS-70 program, suitably braced and provided with extra current feeds as shown in Figure 5, was used for the early tubes in the MAPS-40 program. While this cathode was capable of supplying the necessary peak current, completion of an entirely new design (Figure 6) was necessary. Its design objectives were:

1. Improved utilization.
2. Improved storage and distribution of the operating dissipations.
3. Better thermal efficiency.
4. Prevention of thermal runaway through careful design of welds and current feeds.
5. Mechanical ruggedness.
6. Independence of the cathode from all mechanical and electrical connections to the heater.

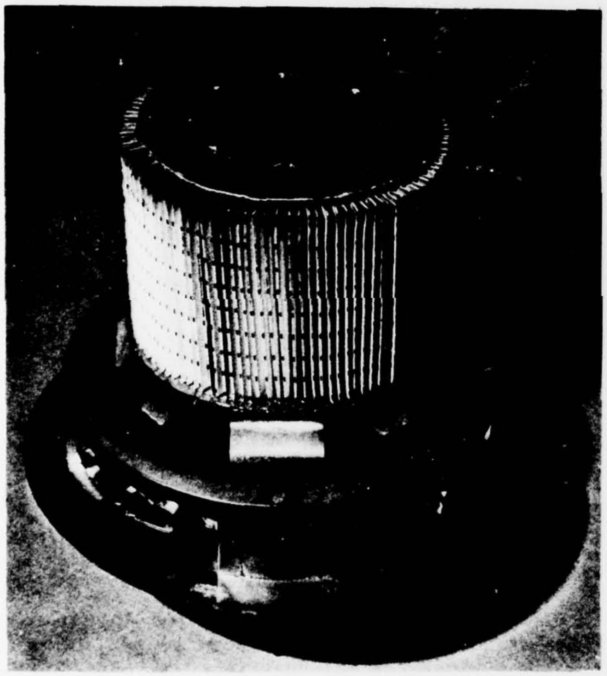

Figure 5. Early MAPS-40 cathode structure.

The thermal mass of the cathode, together with its radiative and conductive properties, allows it to absorb the high operating dissipations encountered during "on" cycles and to disperse them to the surrounding structures and tube exterior during "of " cycles. Vanes covering the upper face and the sloped contour are intended to improve cathode utilization. The vanes are held and spaced by slots in both the support structure and the circumferential band, made of Hastelloy B. Figure 7 shows the nickel vanes fitted to the Hastelloy support structure. No base-plate or cylinder is used between the vanes and the central heater: heat transfer is by direct radiation and gas conduction from the heater to the emitting surfaces of the vanes, an arrangement which allows both efficient use of a cool-running heater, and the prompt redistribution of possible localized heat buildups due to operating dissipations. Individual welding of each vane, illustrated in Figure 8, to the annular current-feed ring assures uniform electrical current distribution, while the stiff cylindrical understructure provides support and restricts conducted heat losses to a tolerable level.

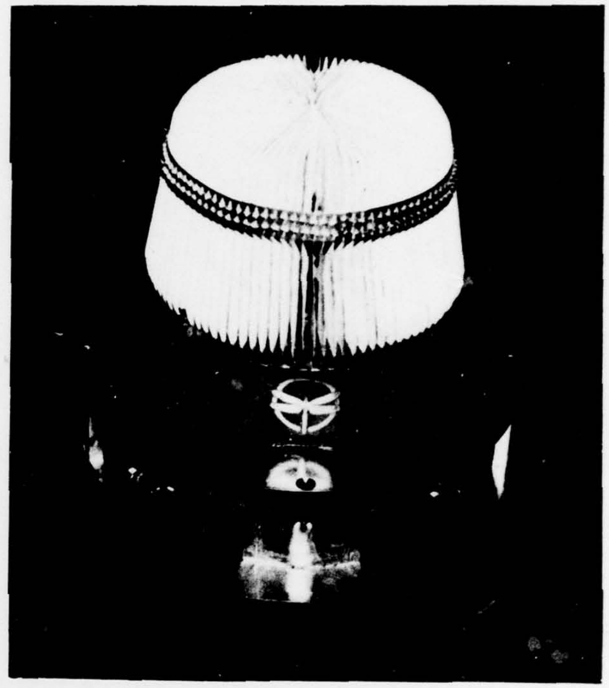

Figure 6. Cathode design developed for MAPS-40.

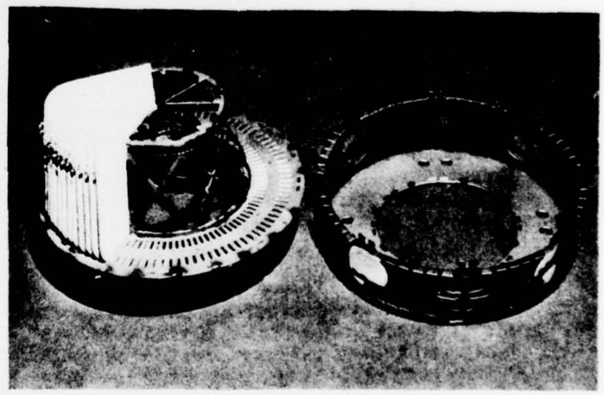

Figure 7. MAPS-40 cathode support structures.

As a bell-jar test, a one-eighth pie-wedge sector of the cathode was isolated electrically and heated to the estimated maximum operating temperature in vacuum by means of the cathode heater. The output of a 200-ampere arc-welder was then connected across it through a current distributing harness. An examination was made for hot-spots or signs of thermal

runaway, a test equivalent to 1600 amperes rms-equivalent through the complete cathode. No signs of distress were observed.

As an environmental test, the entire cathode structure, thoroughly annealed by prolonged test runs at operating temperature, was bolted to a test bed and subjected to 10-g vibration at 50-2000 Hz, and to 100-g shocks in the axial and orthogonal planes. No major resonances were observed and no deformation took place, a distinct advance over the earlier MAPS cathode structures.

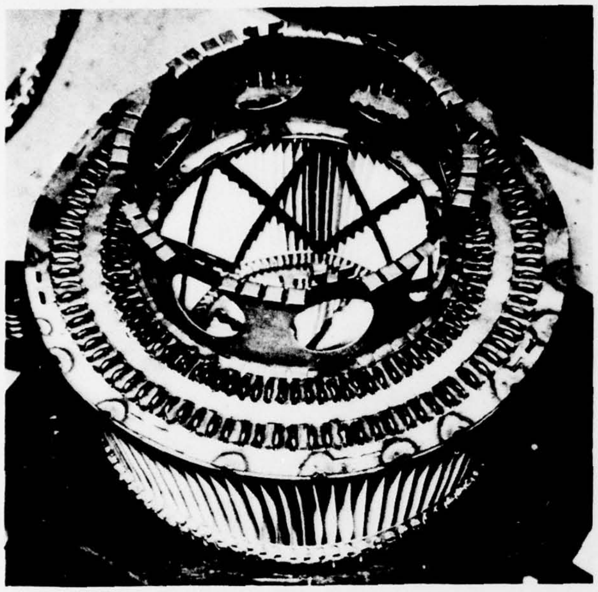

Figure 8. Cathode vanes individually welded to current feed ring.

Heater

Previous experience indicated that it was best to run the heater at a relatively low temperature, and to separate it mechanically and electrically from the cathode structure. The area available for heat transfer inside the cathode vane structure is small; therefore, severe demands are made on the design of the heater.

The heater shown in Figure 9 is a cylinder of vertically pleated molybdenum mesh, assembled from four quadrants, each with its own head and tail current feeds, which are connected down at the bottom of the structure, well away from the hot-zone. Toothed "gears" made of ceramic-covered molybdenum support the pleats both internally and externally, preserving their spacing and bracing them against lateral and torsional vibration.

This heater has withstood 75 cycles at three times the design power, followed by pounding on the bracing structure with a hammer and further cycling, without shorting or fracture. Its net emissivity to the surrounding vane structure at operating temperature is 0.78.

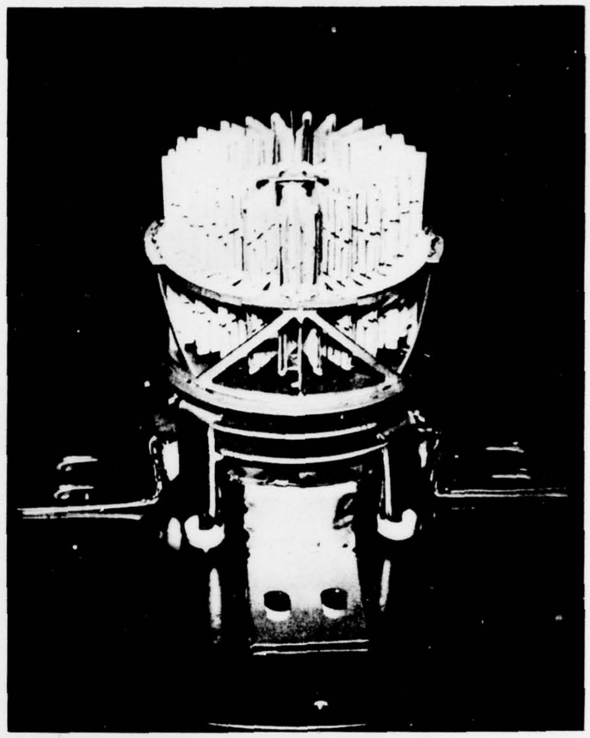

Figure 9. MAPS-40 cathode heater.

Reservoir

Transient cleanup was suspected to be a problem during burst-mode operation, with very little time available to readjust the pressure. A fast-acting reservoir able to respond quickly to pressure and heater-power changes was required. The reservoir used in the MAPS-70 had these desirable characteristics, but it was fragile and unstable. After much effort, the reservoir was redesigned.

The MAPS-40 reservoir shown in Figure 10 consists of a flat serpentine heater flanked by two sets of titanium strips stacked edgewise. The resulting sandwich is packaged in a lightweight, open frame, where it loses heat primarily by radiation and gas conduction. Run hot, at a relatively low specific loading, the reservoir responds quickly to changed conditions at a rate determined only by power, mass, and specific heat considerations. A complete reservoir consists of four of the units shown, a total mass of 400 grams of titanium loaded to approximately 500 liter-torr total of deuterium at 0.3 torr equilibrium fill pressure.

The reservoir is isolated from the cathode heater and tube operating dissipations by suspending it beneath a heavy sole-plate, a "false-bottom" connected to the tube base by massive copper bus bars. The sole plate also serves as the current feed and mechanical support for the cathode, which is bolted to its upper surface. All heat reaching the sole plate is promptly conducted out through the base of the tube.

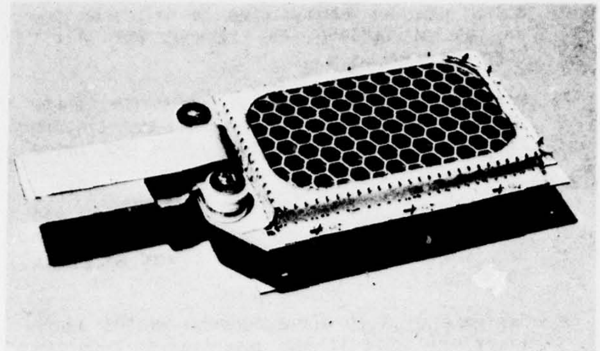

Figure 10. MAPS-40 reservoir.

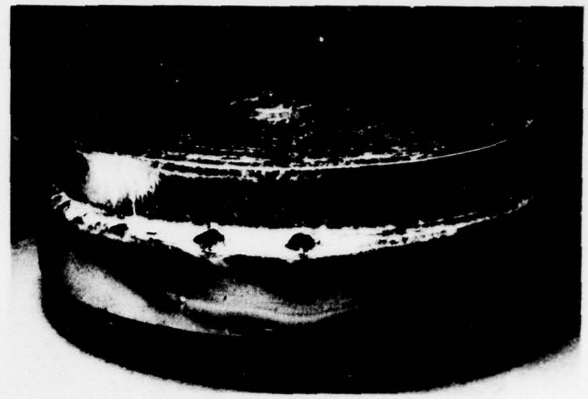

Figure 11. Damage to anode shield.

Aging and Testing

After assembly and processing, the tubes were given a preliminary aging and test at EG&G in Salem, Mass. They were then shipped to the high power test laboratory of the US Army Electronics Command, in Fort Monmouth, New Jersey, for further aging and final testing.

In the first phase of the program, of five tubes shipped, four were selected for full power test and evaluation. The procedure consisted of bringing the tubes up to the 40 kV, 40 ka operating level, and then increasing the repetition rate in stages to give successively higher average power levels. Sufficient time was allowed at each stage for the tube to stabilize and adapt itself to the increased demands made upon it. The aging time per tube varied between four and ten hours, while the number of kick-outs ranged from a low count of two to about thirty.

Aging and running-in proved to be a critical process, due to the prevalent possibilities for sudden catastrophic failure in both tube and test circuitry at the power levels involved. Here, phenomena such as anode overheating or glow-spots could rapidly assume serious proportions when the energy responsible for them became concentrated in one spot. Protecting the test instrumentation from conducted spikes and stray fields was a critical problem. As experience was gained in getting the tubes to run, the final tubes in the series became relatively easy to bring up to full power.

The following necessary precautions were taken:

1. Careful monitoring of the tube anode, envelope, and seal temperatures, and use of adequate and symmetrical forced air cooling.

2. Visual observation of the anode and the entire 360° of envelope circumference to catch sudden overheating, glow-spots, and other troubles before they became severe.

3. Attention to tube pressure to avoid catastrophic tube failure from hydrogen starvation. Figure 11 shows a hole burned through the anode shield by excessive dissipation due to low deuterium pressure.

4. The use of a distributed-current feed, as shown in Figure 12A, was essential to keep magnetic fields from pushing the internal tube discharge into the walls and structures,

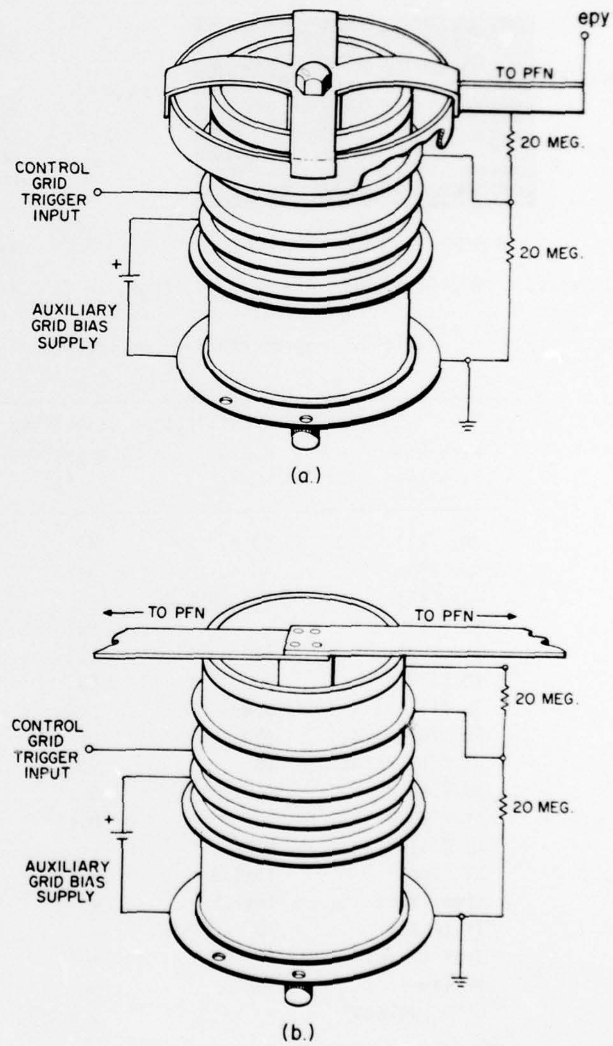

Figure 12. Distributed and symmetrical current feed.

where it could degrade holdoff and cause considerable damage. The problem is now avoided entirely by use of a symmetrical feed from the pulse forming network (PFN) as shown in Figure 12B.

5. Use of inverse clippers. As expected, the tube did not display any inverse holdoff capability. Figure 13 shows inverse breakdown occurring at only 2 kV.

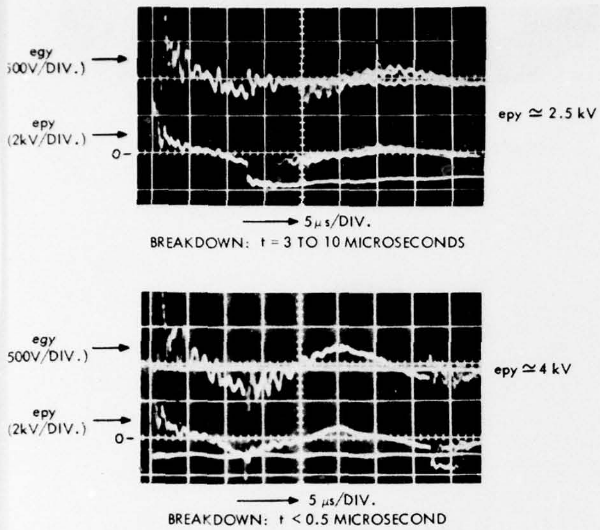

Figure 13. MAPS-40 inverse breakdown voltage.

6. Allow generous warmup time to help overcome an initial tendency to kick-out when first starting up.

7. Monitor the temperature and resistance of the copper solution used as a load to maintain the proper ratio of load to PFN impedance during tube operation.

8. Use of thyrites in the cathode heater and control grid leads to prevent spikes from getting into the filament and trigger supplies.

9. Presence of keep-alive current in the auxiliary grid circuit was essential in reducing tad and jitter.

Operation at the full megawatt power level produces brilliant red bands of hydrogen Balmer-alpha light which encircles the tube envelope, accompanied by a heavy hammering at the repetition rate. It is obvious that much is being demanded of both tube and test circuit at this power level.

Test Results

Specification Objective Tests

Representative test results for the first four tubes evaluated at the full megawatt average power condition at Fort Monmouth are indicated in Table 3, which compares the original specified objectives with observed performance.

Once aged in and running, both the original four tubes tested and the subsequent seven tubes built under this program operated within specified limits. Trigger voltage was typically 2000 volts, well within

Table 3. Representative performance of developmental MAPS-40 thyratrons.

Parameter (Units)	Specification Objectives Rating	Operation (1)	Representative Performance Full Power Test	Special Tests (1) Highest Peak Current	(2) Continuous Operation	(3) Highest Voltage
epy (kV)	40	44	44	40	36	50
ib (kA)	40	44	44	75	36	50
egy (kV)	1.5 to 4.0	–	2	–	–	–
tp (μs)	–	10	10	–	–	–
prr (Hz)	500	125	125	–	77	50
Ib (A dc)	50	50	50	–	20	24
Ip (kA ac)	1.48	1.48	1.48	–	0.85	1.1
Pb (10^9 va/s)	400	242	242	–	–	–
dik/dt (kA/μs)	20	20	20/40	75	36	50
td (μs)	–	0.2	<0.2	–	–	–
Δtad (μs)	–	0.1	<0.1			
tj (μs)	0.02	–	<0.02			
Ef (Vac)	15±1.5	–	–			
Eres (Vac)	15±1.5	–	–			
If (A ac)	70	–	66			
Ires (A ac)	40	–	40			
tk (sec)	900	–	1200			
Life (pulses)	–	5 x 10^6	*			

*0.3 x 10^6 pulses achieved to date without discernible change in performance.

the specified range. The anode delay time of 0.2 microsecond was met with the aid of an auxiliary keep-alive current of 50 ma. (Measurements indicate a tad of much less than 0.2 microsecond.)

Due to temporary test equipment limitations, none of the existing tubes has been tested to the full thirty seconds of "on" time in burst mode at 40 kV. They have been repeatedly run, however, at this voltage for "on" cycles of 10 and 15 seconds, and in other tests, they have been subjected to a full 30 seconds at 30 kV and 0.56 megawatt, and have also been run for 10 seconds at 45 kV and 1.27 megawatt. The capability shown so far augurs well for success in the full 30-second burst at 40 kV and 1.0 megawatt.

Representative values for temperature rise during burst-mode operation are shown in Table 4. The relatively modest temperatures reached and the small spread between them shows that the thermal loads are well balanced and not excessive.

Table 4. Temperature rise at megawatt average power MAPS-40 Tube No. 10 — 10 second "On" cycle.

Temperature Probe Location	Temperature, °C Start	Finish
Cathode Enclosure	120	210
Cathode — Auxiliary Grid	135	255
Auxiliary Grid — Control Grid	100	220
Control Grid — Gradient Grid	65	150
Anode (avg.)	35	180
Final Temperature Spread	—	15

Other Tests

Additional information was obtained in the course of exploratory tests of the nominal design limits.

In a peak current test, the thyratron was operated into a 0.25-ohm load at 40 kV, switching a peak current of 75 ka. The 70- to 80-ka ultimate design limit due to quenching was confirmed.

In an average current test, the thyratron was subjected to continuous operation for 30 minutes at 40 kV and a pulse repetition rate of 50 Hz, giving an average current of 20A. The thyratron operated well throughout this interval, but additional cooling was required. While incapable of confirming the expected 30A average current capability for continuous operation, this 20-ampere, 30-minute run established a benchmark for high average current operation.

In a high voltage test, one tube was run at 50 kV at the 0.5 megawatt power level without difficulty, showing that the single gradient grid will allow higher voltages to be reached at these power levels.

Warm-up behavior was explored in a separate test wherein a tube was operated in a standard 2.5-microsecond, 7-ohm, 400-Hz thyratron test set. A standard 2400V, 50-ohm driver was used, with the auxiliary grid tied to ground through a 30K ohm resistor. The following results were obtained:

	Ef (Vac)	If (Aac)	Eres (Vac)	Ires (Aac)	epy (kV)	Elapsed Time (min.)	tad (μsec)
Run 1	15	63	12	37	15	15 (T_k)	3.0
	15	63	13	39	40	25	1.3
	15	63	14	43	40	50	0.14
Run 2	16	68	14	43	25	7 (T_k)	0.8
	16	68	14	43	40	8.5	0.72

Minimum Ebb was 4kV.

Conclusions

Of the eight thyratrons constructed in the first phase of the MAPS-40 project, four were tested successfully against the specification objectives at the megawatt power level. Seven additional tubes have been constructed and tested, all of which met the specification objectives at this power level. While further exploration of the design limits needs to be done, including a full 30-second run at 40 kV, it is already apparent that the MAPS-40 can be rated for burst-mode applications at the megawatt average power level, and for high power continuous repetition-rate operation as well. The tube is producible, and the thermal and mechanical features are capable of extension to still higher power levels. The MAPS-40 gives the pulse power circuit designer the option of employing the well-known advantages of the hydrogen thyratron for switching at megawatt power levels.

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This paper gives a very partial account of integration theory in Hilbert space and related questions of absolute continuity which may be important in problems of stochastic realization theory, linear and non-linear filtering, detection theory and quantum communication theory. The need for such a theory arose for the purpose of putting quantum field theory on a rigorous mathematical basis. The theory has a distincy algebraic character and is particularly suited to the needs of stochastic system theory. This theory is different from the work of the Russian school in the sense that essentially

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20. Abstract continued.

Hilbert space techniques are used and in general one works with "weak" processes as opposed to "strict" processes. In this theory non-linear functions of processes can be handled and in particular certain non-linear functionals of white noise can be given mathematical meaning.